A study of MFL signals from a spectrum of defect geometries

Neil R. Pearson¹,², Matthew A. Boat¹, Robin H. Prewald², Matthew J. Pate¹,², John S. D. Mason²

¹Silverwing UK Ltd; Unit 31 Cwmdu Industrial Estate, Swansea, SA5 8JF, UK; e-mail: npearson@silverwinguk.com
²College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

Abstract

A primary reason for failure in above ground storage tanks (ASTs) is corrosion. The inability to accurately define defects caused by corrosion, particularly those located on the AST floor, can lead to erroneous repair strategies with costly outcomes. Therefore, accurately determining the geometry of defects is pivotal if an appropriate repair strategy is to be formulated.

Magnetic flux leakage (MFL) is a widely used and accepted technology for locating defects on a tank floor. While MFL signals are often linked to the volume of a defect, its depth is perhaps the most difficult and critical to estimate since it indicates the closeness of a potential leak.

In this paper we look to establish a relationship between the defect and the corresponding MFL by analysing the influence of two fundamental components of the defect geometry, namely the length and the depth.

Keywords: Magnetic flux leakage (MFL), defect characteristics, defect normalisation, defect geometry.

1. Introduction

Magnetic flux leakage (MFL) is a widely used non-destructive testing approach to detect corrosion and pitting defects in carbon steel structures. MFL for the inspection of above ground storage tank (AST) floors was proposed in 1988 by Saunderson [1]; its key benefit is in being able to cover large areas quickly, providing an alternative to the tedious and sparse ultrasonic spot checks that was standard practice at the time. Current practice employs MFL to screen the floor for potential defects and use the resulting maps to estimate the localised material loss. To provide a more thorough report, MFL scans are supplemented with more detailed ultrasonic spot readings in regions where steel loss has been detected¹. The reason for this is that MFL signals are "more closely related to volume of metal loss than to the depth of pitting" [1]. In the context of ensuring containment, clearly the depth is the critical dimension, because it indicates the closeness to the occurrence of a leak. Clearly this two stage approach of MFL scanning followed by localised ultrasonic examination incurs additional time and expense, which can be significant when large areas are concerned.

While speed of scanning is an advantage of MFL, the resultant signals can be difficult to interpret. As described by Charlton [3], the difficulty arises as a consequence of the complex and potentially ambiguous relationship between the MFL signals and the underlying geometry of defects. With this in mind, consider Figure 1, which shows two purposely chosen defects with very different depths. The MFL signal amplitudes coming from these defects have similar characteristics, even though the underlying defects themselves are quite different. This example shows that relying on the MFL signal amplitude alone to ascertain the severity of a defect can result in serious ambiguity, particularly when narrow and deep pipe type defects are concerned. This is the problem we address in the paper, namely the relationship between MFL signals and true geometric representations of the corresponding defect, focusing on its depth. The main contributions of this paper are to show when ambiguities arise as the defect shape is varied and provide a more complete picture of the non-linear relationship between MFL signals and defect geometries.

The next section provides an overview of related work in the context of MFL signals and defect geometry. Section 3 describes the set-up of the MFL system and Sections 4 and 5 present experimental results describing the signals coming from variations in the defect depth and length respectively.

¹A recommended practice guide in the UK was presented to the health and safety executive in 2006 and it is still considered good practice to supplement MFL with a quantitative inspection technology such as ultrasonics to obtain an accurate assessment of the defect, in particular its depth [2].
Figure 1: Two surface defects and their corresponding MFL signals. Profiles (a) and (b) illustrate defects with respective depths $d$ of 90% and 40% on a 6 mm specimen. These profiles have corresponding lengths $L$ of 3 mm and 22 mm. The amplitude of the corresponding MFL signals show little difference in the amplitude which can, if misinterpreted result in severe pipe type corrosion not being repaired.

2. Related Work

The majority of related publications analyse the relationship between MFL signals and their corresponding defects with the aim of extracting characteristics such as the width, length and depth and reconstructing the defect profile. Most authors who have attempted to model such relationships suggest that it is non-linear both within and across these three dimensions.

The pioneering works of Atherton and Daly [4] in 1987 and Charlton [3] in 1995 chiefly reinforce the non-linear findings described by the early work of Saunderson [1]. In the context of pipeline inspection, Atherton and Daly [4] attempt to ascertain the characteristics from MFL by means of simulation. They examine the MFL signals coming from defects with a common width and length while their depths are varied linearly from 0% (no defect) to 100% (through hole). The investigation reveals that a near-linear relationship exists when the defect is varied up to 60% in depth. However, the MFL signal amplitude for defects that are above 60% rise at an accelerated rate, resulting in the reported non-linear relationship. The sharp rise was due to the design of the magnet assembly, which can have a significant impact on the characteristics of the MFL signal; an important observation that is considered later in this paper.

Whilst performing similar work, Charlton [3] reinforces Saunderson’s [1] comments about the volume of defects. When varying attributes of the defect shape, Charlton comments that with “defects of the same depth and orientation with experimental measures of different shape artificial anomalies, an almost linear dependence upon the volume of the defect and the flux leakage magnitude was obtained”. These observations led Charlton [3] to develop a simple defect scaling approach resulting in a predefined look-up table. This look-up table is formed from a set of controlled reference measurements with emulated defects, a practice still used today [2].

In 2006 and in the context of pipeline inspection, Qi et al. [5] provided a comprehensive study concerning variations in the MFL signal when the geometric parameters of the width, length and depth of a defect are varied. Qi et al. [5] demonstrated the difficult task of characterising MFL signals, in particular the non-linear contribution when varying different defect geometries. In [5], Qi also shows that characteristics of the length of a defect can be extracted with high accuracy from a sub-set of MFL signals. Again, the same length attribute is discussed by Siebert
and Sutherland [6] and reported to be a reliable and quantifiable measure. The length can be determined from the lateral distance between the positive and negative peaks of the normal component of the MFL signal. It was also observed by Qi et al [5] that the depth of the defect, being the most crucial parameter for repair is also the most difficult to estimate.

Also in 2006, Zuoying et al. [7] analysed the relationship between the peak-to-peak value of the MFL signal across a set of defect geometries with the aim to "provide training data for automated defect characterization schemes". The authors in [7] report that if only the depth is varied then the MFL peak-to-peak “is strongly related to defect depth” and that “the relationship between the defect depth and MFL [peak-to-peak] are near linear”. While this does slightly contradict the early pioneers, it should be noted that only a limited geometry is considered and the findings do not generalise well.

In 2007, Qi [8] further demonstrates the capabilities of the MFL approach. In particular, Qi shows that when the length and width of defects are varied, the amplitude of the MFL signal also varies. This variation is illustrated well by Qi who hints at a complex relationship that interleaves the three defect geometries. Again, the depth measure is identified as the “most critical of the three” [8] for repair and empirically the depth is identified as the most difficult dimension to establish accurately. This difficulty was observed when geometries, aside from the depth, were changed, the amplitude of the corresponding MFL tended to vary in a non-linear fashion. Thus, estimating the depth from the amplitude alone is likely to prove impossible for many cases and other parameters such as the width and length parameters are needed. This supports the early comments of Saunderson [1] that the amplitude of an MFL signal is a function of the corresponding defect volume.

More recently in 2010 and in the context of pipelines, Saha et al. [9] proposes an analytical function to describe the relationship between the MFL signals and the width and length of defects in order to ascertain their depth. The defect length is obtained by Saha et al. from the lateral peak-to-peak measure of the corresponding MFL signal; a measure that is reported in the earlier work of Siebert and Sutherland [6] as a “crisp definition of defect length”. With length dimensions established, Saha et al. [9] continues to establish a measure of the defect width, giving rise to a function that leads to the calculation of a width to length ratio. From a subset of defects, a relationship between the width and length is then established; a relationship which is reported to be “predominantly a linear function” [9] in the context of narrow, pipe type defects. Furthermore, when estimating the depth in conjunction with the width and length function, defects that were considered general corrosion tends to be oversized in error by no more than 5%. Saha et al. also comment on the relationship between MFL and defects and that ambiguities can occur, commenting that “the mapping between signal to defect parameters is in general non-linear” and that a “many-to-one mapping complicates the situation further” [9]. However, in [9], Saha et al. provides no further reference or examples about these many-to-one ambiguities.

3. Signal acquisition and the shapes of defects

To inspect a ferrous specimen with MFL, the local area of interest is saturated with a magnetic field. In the absence of material, the reluctance of the magnetic field path increases and if high enough the field will be forced to diverge. This field can diverge around the absence within the parent material and also ‘leak’ into the surrounding environment. The quantity of the leaking magnetic field is then measured by suitably placed magnetic sensors. To perform rapid inspection of an AST floor, a scanner normally has a linear array of sensors, orientated perpendicular to the direction of travel. In this work, MFL signals are considered as if received from a single magnetic sensor and have been generated via 2D finite element modelling. Only rectangular defect profiles are considered, allowing the geometric depth or length to be adjusted readily and independently.

The induced magnetic field can be simulated in two ways, either by (a) approximating the set-up of an MFL machine, such as the yoke design or (b) a homogeneous magnetic field where factors attributed to the yoke, for example its design and lift-off parameters [10] are normalised. The latter approach (b) is adopted here with a suitable magnetic field strength to saturate a 6 mm steel plate; the homogeneous field is such that it is fixed in the plate at two Tesla. The MFL signals are extracted 3.8 mm above the top surface of the specimen and orientated to collect the Y component of the magnetic flux density \( \mathbf{B} \) (where \( \mathbf{B} = (B_x, B_y, B_z) \)) at regular intervals. Also, due to the relatively low speeds of the scanners, namely a normal walking pace of approximately 500 mm/s, a magneto-static analysis is appropriate [3, 11, 12]. Other factors which can influence the MFL signal include permeability changes in the
specimen, adjacent defects [13] and cleanliness of the inspection surface, all of which, for this work, are assumed to be non-intrusive or normalised.

4. Influence of defect depth

In this section we consider the influence of only the defect depth on corresponding MFL signals and in the context of a single step as shown in Figure 2.

Figure 2: Monotonic step profile in (a) can be varied by depth ‘d’. The amplitudes of the corresponding MFL signals $B_y$ in Tesla are shown in (b) as a function of sensor position ‘$i$’ in mm over a distance ‘$I$’. The amplitude of these profiles increase as ‘$d$’ is increased from 1 % to 100 %. In (c), the peak amplitude of each MFL signal in (b) is plotted as a function of the depth of the defect. This profile illustrates the non-linear nature of MFL with respect to the depth of a defect at the edge of a defect.

Figure 2(b) illustrates a collection of $B_y$ MFL signals acquired from a set of corresponding monotonic step profiles as a function of the position ‘$i$’ of the magnetic sensor across its surface. Defect depth ‘$d$’ varies from 2 % to 100 %, i.e. a plate edge in the monotonic context. In this set-up, the largest amplitude MFL signal comes from the 100 % step transition and has an amplitude of approx. 0.166 T.

Notice in Figure 2(b) the influence of the MFL signal coming from a 100 % step profile extends to about 60 mm from the step edge. This extension implies that the MFL has a relatively low frequency response, i.e. many of the fast transition components of the sharp step profile are removed or filtered. The frequency response of an MFL signal was briefly demonstrated by Ramirez [14] who reported that no frequencies above 50 Hz were found when travelling at 500 mm/s. This is an avenue that perhaps warrants further investigation.

In Figure 2(c), the peak amplitude of each MFL signal from Figure 2(b) is plotted as a function of the depth of the step. In Figure 2(c) there is a non-linear increase in the MFL signal as the monotonic defect becomes deeper. Similar observations were reported by Charlton [3], “for any given nominal plate thickness, the variation in flux leakage magnitude increases as a function of defect depth”.

A simple reference scheme can be established from the profile exhibited in Figure 2(c) to map the amplitude of a given MFL signal to the corresponding depth. However, a reference scheme based on monotonic defects is perhaps of limited use, since in the context of real corrosion, a defect will always contain some form of adjacent edge. This
edge-to-edge measure defines the length \( L \) of a defect and its influence on the MFL signal is considered in the next section.

5. Influence of defect length

Figure 3: Non-monotonic defect with a rectangular profile in (a) varies in length \( L \) from 1 mm to 200 mm. The corresponding MFL signals for each defect length is illustrated in (b); in this instance, only MFL signals from a defect with a depth of 70 % are shown. The profile in (c) reflect a measure of the peak amplitude from each MFL signal in (b) as a function of \( L \).

Figure 3(a) shows a rectangular defect of fixed 70 % depth \( d \) and length \( L \). As \( L \) is varied from 1 mm to 200 mm the corresponding MFL signals as a function of the corresponding sensor position \( i \) are illustrated in Figure 3(b). The profile in Figure 3(c) is a measure of the peak-to-peak amplitude of the MFL signal from the central sensor as a function of the defect length \( L \). When \( L \) increases beyond 40 mm, it can be seen that the corresponding peak-to-peak amplitudes reach a steady-state or plateau, making the depth estimate trivial in this region. However, as with the bipolar peak-to-peak amplitude measure, Ji et al. [10] reported that \textit{"as the [defect] length increases, MFL peak-to-peak will increase"}, a trait that can be observed in Figure 3(c) but only when the peak amplitude of the MFL signals come from defects that have a length below 40 mm. This variability in amplitude, as a function of length, corroborates the observation of Charlton [3], \textit{"the flux leakage magnitude was more dependent upon its area [analogous to the length in 2D] than its depth"}.

The peak amplitude measure presented in Figure 3(c) is plotted in Figure 4(a) along with additional defect depths of 20 %, 50 %, 80 % and 90 %. A profile with similar shape is observed for each depth and each profile appears to be a scaled representation of one another; note the inclusion of the depth component adds a further ambiguity.

Figure 4(a) shows plots for different depths \( d \), as in Figure 3(c), the non-linear response is repeated for each depth when \( L \) is below 40 mm. The lower signal amplitudes coming from such defects correspond to the observations of Marino and Drury [15] who report the difficulty of detecting such defects with MFL. One reason for this difficulty is the reduced reluctance path of the induced magnetic flux between the edges of narrow defects. The low magnetic reluctance between the edges allows a significant proportion of the flux to ‘jump’ directly between them causing a reduction of the MFL signal in the vicinity of the sensor.
Figure 4: (a) shows five profiles from non-monotonic defects of depth 20%, 50%, 70%, 80% and 90% reflecting the peak MFL signal amplitudes. Each profile is a function of a non-monotonic defect varying in length \( L \), again varying between 1 mm and 200 mm. (b) illustrates the potential ambiguity of defect depth and length combinations (i), (ii) and (iii) from a single MFL amplitude. Unfortunately, many natural defects found on the floors of ASTs exist in this non-linear region and thus ambiguities can occur; examples of such ambiguities are illustrated in Figure 4(b) where the abscissa is reduced in range to 50 mm. For a given MFL amplitude, three example ambiguities are illustrated and so the MFL signal could relate to defect (i) where ‘\( d \)’ is 90% deep with ‘\( L \)’ being 4 mm, (ii) 70% and 6 mm or (iii) a 50% deep defect that is around 17 mm in length. This illustrates the potential error and difficulty when interpreting the defect depth, in particular from MFL signals coming from narrow defects.

6. Conclusion

MFL is a rapid and robust approach that is well suited in ascertaining the general condition of AST floors. One limitation of the MFL approach is the inability to accurately size defects once they have been detected, resulting in the need for further manual examination. While MFL signals from recent work have attempted to enhance the interpretation of defects and give indication of its shape, MFL signals from a narrow, pipe type defect remain difficult to classify.

Over the set of defect geometries considered in this paper, two key non-linear traits have been identified: those attributed to the depth of the defect and those attributed to its length. Additionally, these attributes, when combined tend to add further complexity. The defect depth/length map presented here demonstrates the potential MFL signal ambiguity across defects that are 90%, 70% or 50% deep.

This paper has shown that defects with a length in excess of 40 mm do not exhibit the depth ambiguity associated with MFL signals. Given the circumstances of a constant value MFL amplitude and an increasing defect length the MFL amplitude is seen to reflect the defect depth quite well and therefore cannot reflect the defect volume.

Acknowledgements

This work is funded by Silverwing UK Ltd.
References